A Data-driven Fuzzy Front End Model
for Contextual Performance and Concurrent Collaboration

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Abstract

A data-driven model for the Fuzzy Front End (FFE) stage in new product development (NPD) programmes, with a series of toolkits to decrease uncertainty and ambiguity of parameter processing, has been developed. Parameters produced in toolkits provided in previous models tend to exist independently, without any interrelationship in the contextual performance relationship of a single functional domain nor concurrent collaboration relationship across multiple functional domains. This results in uncertainty and ambiguity triggered by an incorrect interpretation of parameters. The new model involved inferring a single representative FFE scenario wherein diverse FFE performance structures interlock from the contextual performance and concurrent collaboration perspectives by analysing various real-world FFE scenarios gathered from NPD expert interviews. This representative scenario was embodied into the model with a performative structure, through deployment of toolkits. Users are informed of the purpose, roles and meanings of parameters and their relationships and thus can infer each parameter from other parameters. This contributes to reduction in uncertainty and ambiguity in processing parameters. The study proposes an FFE execution concept, giving mathematical reasoning behind the performance structure of the model.

Keywords: Design, Product, Development, Specification, Collaboration, Fuzzy Front End, Uncertainty, Ambiguity

Managerial Relevance Statement

This study proposes a data-driven fuzzy front end (FFE) model and an associated FFE execution concept, for industrial application.

The data-driven model has a performative (toolkit) structure wherein all NPD-related parameters produced in the toolkits interlock for contextual performance and concurrent collaboration throughout the FFE phase. When processing and deciding parameters on a component basis using the model itself, the model enables users to explicitly understand the purpose, roles, and meanings of toolkits and parameters produced, and their relationships, in not only a single functional domain but also multidimensionally across diverse functional domains. This allows decreasing uncertainty caused by obtaining an insufficient quantity of parameters from missing the performance of essential activities and toolkits, as well as reduced ambiguity incurred by an incorrect analysis of parameters from interpreting parameters fragmentarily. This results in reducing iterative modification work and associated time and cost savings.

The FFE execution concept, inferred from the performance structure and operating mechanism of the model, consists of a mathematical basis for each FFE task, giving a single concept for the FFE execution.

The data-driven model serves as pragmatic functional performance guidance while the mathematical concept serves as theoretical conceptual guidance when employing the model.

1 Introduction

A New Product Development (NPD) process typically consists of Fuzzy Front-End (FFE), actual NPD, and commercialisation phases [1-3]. In NPD, the FFE is often acknowledged as the most important component [4-6], since more than 60% of the crucial parameters for NPDs are set up here [7, 8]. Nonetheless, this initial design phase is viewed as the weakest part of the process due to the high probability of encountering difficulties when processing and determining parameters [6, 8, 10]. This difficulty comes from the inherent uncertainty and ambiguity of parameters which pervade the FFE to a significant degree [8, 10-12]. Hence, there has been an increase in the volume of FFE studies over the last decade [11, 13-15], including studies which have developed many toolkits, structural and functional framesets in which NPD-related input and output parameters are produced, which consider how the FFE deals with processing and deciding parameters [2, 16, 17].

However, according to our study on toolkits provided by FFE studies published in 1910 to 2020 [shown in the Imperial College London (ICL) Research Data Repository, URL: https://doi.org/10.14469/hpc/7724], most of the FFE toolkits that have been devised so far have specific and critical limitations in their performance structures and operating mechanisms, as follows.

Firstly, few toolkits have been developed with contextual performance (generally activated in a single functional domain) in mind. This means those toolkits do not link to each other but instead have a tendency to be separate and to exist independently for a given purpose and role. Since most of these toolkits have been developed independently for particular FFE activities, they are not systematically connected, and thus output parameters produced from previous toolkits do not enter into the subsequent toolkits as input parameters in a contextual relationship.

Secondly, few toolkits have been developed considering concurrent collaboration (normally activated multidimensionally across diverse functional domains, such as engineering, design and marketing). This means a system structured with those toolkits would not simultaneously involve the FFE activities of multiple functional domains, and thus input and output parameters do not link together in a collaborative relationship.

These structural and functional limitations indicate that the purpose, roles, and parameters of each toolkit cannot be inferred from other toolkits employed in the contextual performance relationship of a single functional domain, as well as the concurrent collaboration relationship across multiple functional domains. It is highly possible that outcomes obtained from each toolkit exist independently, without interrelationship between outcomes produced from other related toolkits. This results in not only a high degree of uncertainty incurred by gathering an insufficient quantity of parameters but also a high degree of ambiguity triggered by an incorrect interpretation of parameters. This gives rise to incomplete parameters which lead to iterative modification work and associated significant time and cost commitments.

This study aims at developing a data-driven FFE model structured with toolkits integrated for contextual performance and concurrent collaboration throughout the entire FFE phase. This model serves as pragmatic functional performance guidance for decreasing uncertainty and ambiguity of parameter processing. This study also presents an FFE execution concept giving the mathematical reasoning behind the performance structure and operating mechanism of the model developed, for guiding theoretical conceptual performance when employing the model.

The remainder of this paper consists, first, of a review of the current toolkit practice. Section 3 presents a research methodology framed in terms of building a model and theory by understanding phenomena. Section 4 addresses the building of the data-driven FFE model by analysing various real-world FFE scenarios and covers an extrapolation of the FFE execution concept from the performance structure and operating mechanism of the model developed. Section 5 discusses the expected contributions on the effects of using the model and concept. The final section addresses potential limitations in this study and future research directions.

2 Review of Current FFE Toolkit Practice

2.1 Data Collection and Analysis Method

This section investigates toolkits provided by FFE processes to establish a direction for toolkit development. The investigation targeted processes developed for the FFE only, generally regarded as covering the early design stage up until the prototyping task [2, 11, 18]. In addition, the initial part of wider processes covering NPD was incorporated [19, 20]. In total 266 FFE processes were gathered using "bibliometrics" focusing on the most cited papers, papers affecting the most cited papers, the most cited authors, as well as the most highly mentioned keywords [19, 21-23], from the 'Web of Science' [19, 24].

To examine FFE toolkits to ensure an accurate reflection of their results in the toolkit development, it is vital to determine how to build specific criteria. The ICL Research Data Repository (URL: https://doi.org/10.14469/hpc/7724) shows four appraisal criteria: 1) Materiality, 2) Functionality, 3) Contextuality, and 4) Cooperability. These four criteria are key considerations in constructing the performance structure and operating mechanism of toolkits. The first and third criteria are associated with the contextual performance aspect, and the second and fourth criteria are related to the concurrent collaboration aspect.

Table 1. Inter-rater agreement between the analyses of the author and the participants

Subject	N of Valid Cases	Inter-rater Agreement (Kappa Values)
Author to Participant 1	4	0.914
Author to Participant 2	4	1.000
Author to Participant 3	4	0.915
Author to Participant 4	4	0.748

Author to Participant 5	4	0.831

Kappa values and strength of agreements: 0.00-0.20: Poor, 0.21-0.40: Fair, 0.41-0.60: Moderate, 0.61-0.80: Good, 0.81-1.00: Very Good

With these four criteria, the toolkits collected were analysed using a peer-review system to reinforce the internal validity of the analysis. An examination was conducted by five NPD experts on an initial batch of ten papers. Papers were compared to each other to see which items matched and which did not, to reach an agreement on the analysis. Until the rate of matched items reached around 80 percent, the discussion continued. **Table 1** presents a statistical analysis of the 'inter-rater agreement', which depicts the level of agreement between the analyses of participants. These statistics suggest a strong level of agreement and thus the conclusion was that the analysis method used was reliable and could be applied to the remaining 256 papers. After examining the toolkit sets provided by the 266 FFE processes in this manner, the results were approached statistically, using the SPSS software package.

2.2 Analysis Result

The ICL Research Data Repository (URL: https://doi.org/10.14469/hpc/7724) shows an analysis table, scatter graph chart and portion table, and provides a full list of 266 FFE processes.

In terms of toolkit development trend, model structures with self-developed toolkits received a great deal of attention in the 1960s and 1970s. It would appear that the development of these toolkits commenced in earnest alongside the development of prescriptive FFE models. From then until the late 1990s, attention on studies about model structures, operation methods, and the correlation between relevant issues were much more stressed, producing both the descriptive and prescriptive model types. Those studies had also tendency to recommend referencing toolkits previously developed; there were very few cases of models devising their own toolkits. With the cross-functional work trend on the rise, there was a tendency to propose many toolkit sets developed in multiple functional fields for use in new models. From the early 2000s, when the potential to represent particular differences in structures and operating systems of models was initiating to decline, efforts to determine how to perform tasks and activities more efficiently seemed to resume. A movement towards offering more specific toolkits reached a peak in the late 2000s. Around this time, many studies on concrete toolkits and their guidelines were carried out, which resulted in various educational materials for a massive set of toolkits.

In the case of the feature of the toolkits, a total of 24 distinct patterns were observed. The analysis indicates that none of the 266 FFE processes provides toolkit sets which fully fulfil all four criteria. In the case of toolkit sets which target only one or two FFE activities from the viewpoint of a single functional domain, those toolkits have components that are comparatively well-connected for contextual performance. However, due to its nature, where toolkit sets cover only a single functional domain, those toolkit sets have weaknesses in concurrent collaboration. Toolkit sets covering the whole range of the front-end from a single functional domain perspective also show the same characteristic. When toolkit sets cover the diverse FFE activities of multiple functional domains in the entire FFE phase, individual toolkits are rarely linked to each other for contextual performance or concurrent collaboration. Most of the FFE processes which provide this type of toolkit set typically referenced and utilised representative toolkits obtained from different existing studies. Therefore, there is an incidence of those toolkits existing separately with a little interrelationship with each other in terms of contextual performance, which also led to difficulties with collaborative work. The more FFE activities and functional domains which are handled with the given toolkit sets, the more limitations there are in the configured structure for contextual performance and concurrent collaboration.

Those limitations have been also revealed in most of the toolkits provided by recent studies including Tate at al. (2018), Khastehdel and Mansour (2018), Cho et al. (2018), Borgianni et al. (2018), Schweitzer at el. (2019), Roach (2020), and Joachim and Spieth (2020) [25-31]. Most of the studies commonly referenced and utilised representative toolkits attained from diverse existing studies. Thus, the toolkits provided tend to exist independently and separate, without any interrelationship, in the contextual performance relationship of a single functional domain as well as the concurrent collaboration relationship across multiple functional domains.

If, from the outset, toolkits are not devised with contextual performance and concurrent collaboration in mind, the toolkits have a high possibility of exhibiting limitations from those two perspectives. Toolkits which involve FFE activities across multiple functional domains or which cover the full range of the FFE need to be developed with contextual performance and concurrent collaboration in mind, from the outset. Otherwise, there is a strong possibility that a newly developed toolkit has structural and functional limitations regarding contextual performance and concurrent collaboration.

3 Research Methodology

This study, as exploratory research, was conducted using inductive reasoning where a new model or theory is built by understanding real-world phenomena [32, 33]. The overall research direction was adopted from a view to building a model or theory (a pragmatic concrete model in this study) from case study research suggested by Stake (2013) [34] under constructivism [35]. In case study research, there are three main streams [35]: a study by Yin (2013) [36] adopts positivism, whereas Stake (2013) [34] and Boblin et al. (2013) [37] embrace constructivism. There are also studies which adopt research worldview that falls in between the two but slightly inclined towards positivism, e.g. Eisenhardt (1989) [38], Eisenhardt and Garebner (2007) [39]; Positivism considers that matter and reality are perceived objectively as independent domains, which indicates that the said matter has objective meaning and exists in and of itself. The perspective of the constructivists which includes interpretivists [34] is that a matter and its reality are constructed differently by different interpretations of individuals in different contexts. Yin's and Eisenhardt's methods have merit in producing a theoretical conceptual model rather than a pragmatic concrete model, while Stake's method is beneficial for developing a pragmatic concrete model instead of a theoretical conceptual model. Considering the research purpose and direction (the development of the pragmatic concrete model), we regarded Stake's method as the most reasonable and appropriate method for this study, under the constructivist's research worldview.

Of the various case study methods recommended by Stake, the interview method was selected due to its merit in gathering accumulation of testimony on the "thing[s]" or "phenomen[a]" which the author has not observed or experienced but interviewees hold [34].

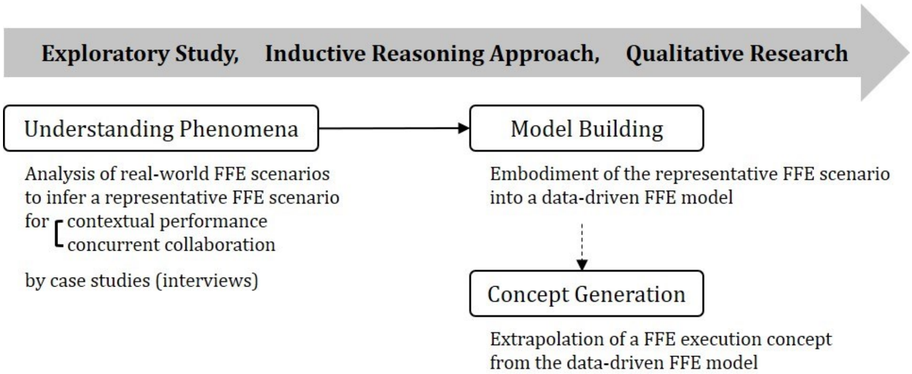

Figure 1. Overall research framework

With the overall research framework (**Figure 1**), the study for a data-driven FFE model development, as a sort of the pragmatic concrete model development, involved analysing various real-world FFE scenarios collected from interviews to infer a single representative FFE scenario organised from the contextual performance and concurrent collaboration perspectives. This representative scenario was embodied into a structural and functional model structured with toolkits integrated from those two perspectives. An FFE execution concept which takes the form of mathematical formulas was extrapolated from the performance structure and operating mechanism of the model developed. The research design, including data collection and analysis method, was evaluated by criteria suggested by Goffin et al. [40].

3.1 Data Collection

Table 2 shows an outline of the data collection method as the interview protocol. Through the data collection method, 57 real-world FFE scenarios were gathered using semi-structured interviews conducted with 38 NPD experts from large corporations, SMEs and government organisations in various consumer product development sectors.

Table 2. Interview protocol (adopted from the studies [34, 41])

<table>
<tr><td rowspan="6">Interviewees selection</td><td>Method</td><td>Stakeholder model and persona analysis</td></tr>
<tr><td>Eligibility</td><td>NPD experts had postgraduate qualifications and worked for more than 7 years</td></tr>
<tr><td>Expertise</td><td>In a specific domain or a multitude of functional domains</td></tr>
<tr><td>Industry</td><td>Consumer product development,
• Including electronics, medical devices and vehicles
• Excluding pharmaceuticals, microchips and software</td></tr>
<tr><td>Number of participants</td><td>38 participants
• participants from large corporations (n=22)
• participants from SMEs (n=12)
e.g. design specialty firms, NPD consultancies
• Participants from government organisations (n=4)</td></tr>
<tr><td>Region</td><td>UK, US, Germany, Netherland, China, Japan and South Korea</td></tr>
<tr><td>Interview structure</td><td colspan="2">Semi-structured interview</td></tr>
<tr><td>Interview pre-test</td><td colspan="2">Conducted 2 times with 3 participants to validate whether the developed interview structure and questions were reasonable</td></tr>
<tr><td>Preliminary Interview work</td><td colspan="2">Provided the interview information and consent pack</td></tr>
<tr><td>Actual Interview progress</td><td colspan="2">• Duration: Took 2 days (around 2 hours per day for each interviewee)
• Mediator: Skype (n=37) and telephone call (n=1)
• Archival Data: Recorded all conversations for producing written scripts
Avg. 20 pages (Times New Roman, 11 points, 1 spaces)</td></tr>
<tr><td>Case Studies
(real-world FFE scenario)</td><td colspan="2">• Number: 57 case studies
• Sector: mobiles (n=5), home appliances (n=23), medical devices (n=17), vehicles, public transit (n=3), furniture (n=5), kitchen utensils (n=4)
• Duration: projects conducted more than 2 months for the FFE phase</td></tr>
<tr><td>Other Data Sources</td><td colspan="2">Toolkits which participants use in their projects</td></tr>
</table>

3.2 Data Analysis

Of the representative qualitative analysis methods – 'Grounded theory', 'Thematic analysis', 'Content analysis', 'Conversation analysis', 'Discourse analysis' and 'Phenomenological Analysis (PA)', the data sets gathered were analysed with the PA method [42-44]. The reason why the five remaining methods are less appropriate to this study (as the pragmatic concrete model development) is described first. Then, the justification of the selected method, PA, is addressed.

Firstly, 'Grounded Theory' [39, 45] and 'Thematic Analysis' [36, 46] are generally utilised under positivism [35]. Those methods consist of coding analysis steps and are generally used to produce a theoretical conceptual model rather than a pragmatic concrete model. These methods are suited to discover patterns which accord with a predefined coding scheme and then convert these patterns into the form of a model. They can miss important and applicable content which deviates from the predefined codes, and thus will not include such contents in the final model form, which tend to produce a conceptual model. Secondly, 'Content Analysis' [47] is also utilised to produce a theoretical conceptual model under positivism [35]. The method is widely used to see particular patterns and frequencies of the repeated contents in participants' responses in order to make generic conclusions by putting everything together in more acceptable for developing a conceptual model. Thirdly, 'Conversation Analysis' [48] and 'Discourse Analysis' [47] are used to developing a pragmatic concrete model under constructivism [35] which is aligned with research worldview of this study. However, the former is more appropriate for extracting connoted meanings from conversations, with consideration in the contextual relationship between the interviewer and interviewee(s). The latter is more appropriate for analyses of the same script which can be differently interpreted depending on the historical, socio-cultural, environmental, and political backdrop. Consequently, the two methods are not suitable for developing a pragmatic concrete model in the NPD industry.

This study used the PA method under constructivism [35]. This method focuses on the phenomenological hermeneutic meanings, phrase by phrase, and clause by clause, in contents of an interview script. The method is of particular help when reconstructing complex information obtained from the qualitative, multiple-case studies, by analysing such information systematically. Analysis outcomes obtained from this method are less likely to skip applicable data which are not highlighted by interviewees but cannot be regarded as trivial. Therefore, this method is appropriate for understanding real-world FFE scenarios to develop a pragmatic concrete data-driven FFE model under constructivism [35].

3.2.1 Four Phases of the Phenomenological Analysis

The PA is structured into four phases and was applied in this study as follows:

1) Phase 1: Reading Through Transcripts

Audio recordings of scripts were transcribed. Then, each script was read through.

2) Phase 2: Defining Meaningful Units

Each sentence was dismantled by the three hierarchical FFE performance structure units defined in studies [50-52] with the number labelling scheme (**Figure 2**).

- ‘Task’: A broadest unit making up the FFE phase.
- ‘Activity’: A subordinated unit to ‘Task’ in that actions aim to accomplish that ‘Task’.
- ‘Performance Method’: Narrative instructions describing how to conduct each ‘Activity’. These manual instructions are later transformed into structural and functional framesets with a performative (‘Toolkit’) structure where input and output parameters are processed.

For instance, in a script, an opportunity discovery task, as the first task in the FFE (Task1), was revealed to exist. One of the activities in the opportunity discovery task (Task1) was an engineering-driven research activity as the fourth activity (Activity 1.4). To accomplish that activity, a performance method to be conducted in the first order (Performance Method 1.4.1) was defining technical functions of each component that make up the product.

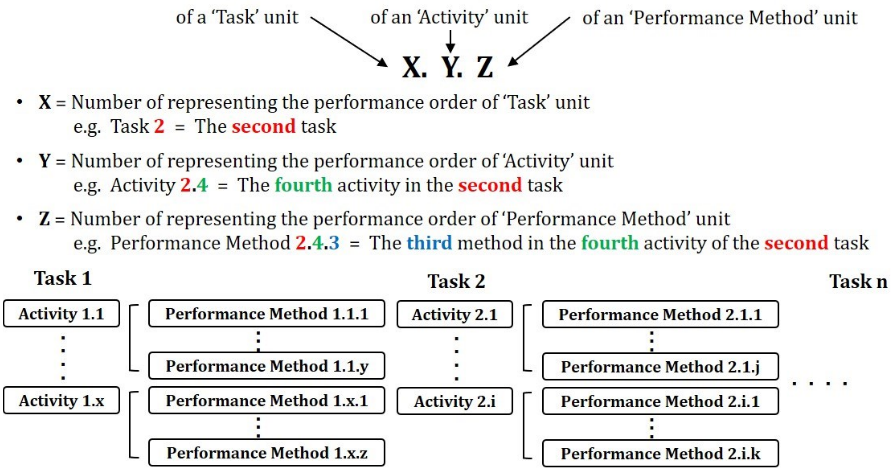

Figure 2. Hierarchical FFE performance structure units with number labelling scheme

3) Phase 3: Transformation

The texts dismantled with the number labelling scheme were aggregated and then classified into the task, activity, and performance method units. The classified units were contextually linked, considering contextual performance and concurrent collaboration.

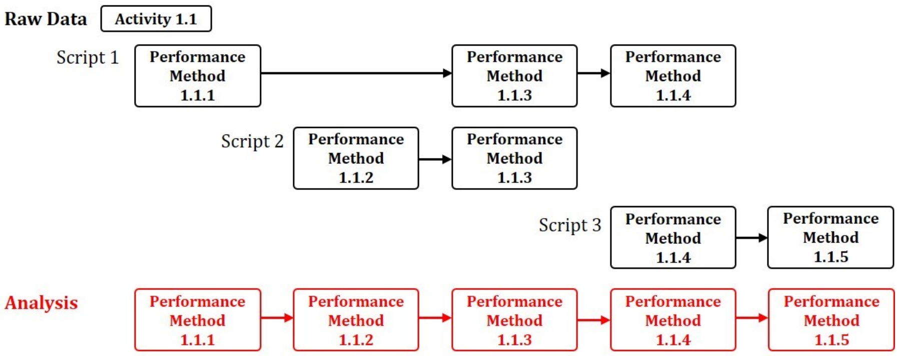

Figure 3. Analysis of FFE performance units
from the contextual performance and concurrent collaboration perspectives

For example, if in one script Activity 1.1 was conducted in the order of Performance Method 1.1.1, 1.1.3 and 1.1.4, and in another script if Performance Method 1.1.3 was implemented based on results of Performance Method 1.1.2, and in yet another script if the outcomes of

Performance Method 1.1.4 affected those of 1.1.5, these three scripts imply that Activity 1.1. can be performed in sequence: Performance Method 1.1.1 to 1.1.5 for contextual performance (See **Figure 3**).

As a further example, if in one script the outcomes of Performance Method 1.2.3 differ depending on the outcomes of Performance Method 1.1.1, and if in another script the results of Performance Method 1.2.3 influence the results of Performance Method 1.4.4, this indicates that Performance Method 1.1.1 in Activity 1.1, Performance Method 1.2.3 in Activity 1.2 and Performance Method 1.4.4 in Activity 1.4 require collaborative work.

4) Phase 4: Structural Description

The contents interpreted in Phase 3 were structurally embodied into a single representative FFE scenario consisting of a series of contextual performance and concurrent collaboration structure.

Figure 4 shows a sample extract from this four-phase analysis.

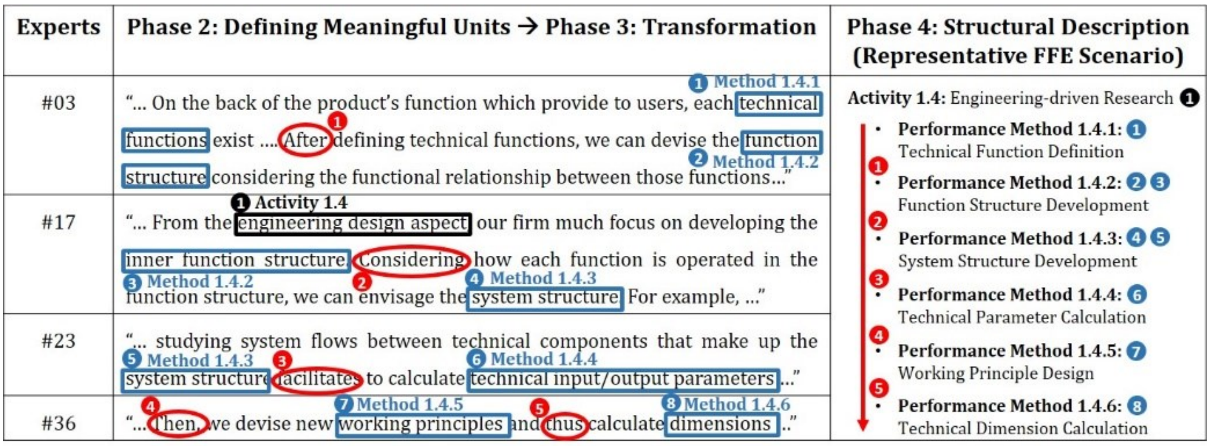

Figure 4. Partial scene of phenomenological analysis

3.2.2 Increase of Internal Validity

Even though the PA process was made to be as systematic as possible, there is a weakness caused by the subjectivity inherent to qualitative data analysis and by bias when interpreting language [53]. Two methods were used to compensate for this.

The first was Stake's 'Triangulation Validation Approach' [34, 54, 55] which fulfils four types of triangulation: 1) 'Data triangulation', where many data resources are gathered and analysed in a piece of research; 2) 'Investigator triangulation', where several researchers and participants are involved in the research; 3) 'Theory triangulation', where multiple viewpoints and theories are used in the research; and 4) 'Methodological triangulation', where scientific methods are used to implement the research. The first and second triangulation types were fulfilled given 266 FFE studies from literature, a variety of product development scenarios and secondary document materials from an appropriate number of interviewees (n=38). The participants selected from various departments (e.g. R&D, design, product planning) of different companies in different countries also helped to reduce "Elite Bias" [52]. The third and fourth triangulation types were satisfied given the well-organised research design from a theoretical and methodological perspective, with many viewpoints on the relationship between research approaches and methods as well as a systematically devised process for the analysis.

The second method was to conduct a peer review system involving five NPD experts to draw an agreement on the analysis approach to be used in the PA method. As a result, the 'inter-rater agreement' which was used in the data analysis of the previous FFE studies suggested a strong level (90%) of agreement between the analyses of the author and the participants, and thus the conclusion was that the method used was reliable and could be applied to this study.

3.3 Model Development and Concept Inference Method

3.3.1 Model Building Mechanisms

The text form of the representative FFE scenario was transformed into structural and functional toolkits that make up the data-driven FFE model. In the process of transformation, this study devised particular model building mechanisms which served as assembly instructions of toolkits for contextual performance and concurrent collaboration.

1) Mechanism 1 for Contextual Performance

Mechanism 1, shown in **Figure 5**, is for structuring toolkits to facilitate contextual performance to better process and determine parameters in a single functional domain. The toolkit structure for contextual performance was built with the following three steps.

Firstly, individual performance method units, identified in each activity unit of the representative FFE scenario, were embodied into the toolkit format which takes the form of a matrix. Secondly, each toolkit embodied was placed on the x axis, following the contextual performance sequences drawn from the representative scenario. Thirdly, the y axis was structured on a product component basis (how to identify components initially is indicated in **Figure 12** and an associated explanation).

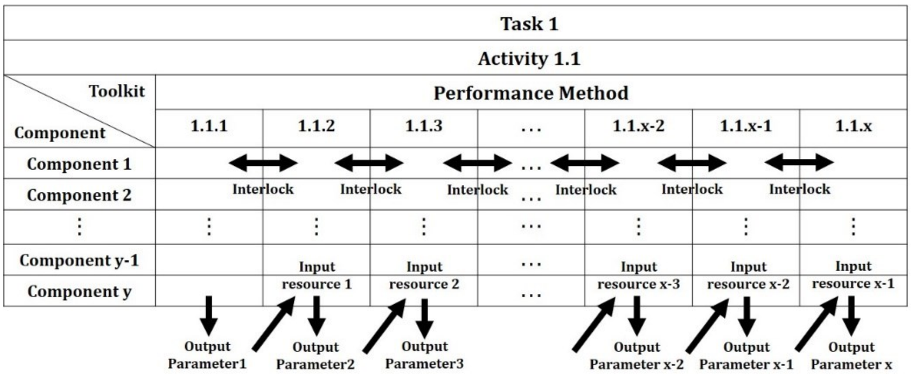

Figure 5. Mechanism 1 for contextual performance

By arranging the toolkits (which have the contextual performance relationship) next to one another, and by enabling interlocking, the output parameters produced in each previous toolkit can enter into each subsequent toolkit as the input parameters. In this way, all toolkits interlock and once users obtain parameters in the first toolkit, parameters for the second, third, all the way to the final toolkit can be obtained in succession for each component, considering the contextual performance relationship.

2) Mechanism 2 for Concurrent Collaboration

Mechanism 2 involves fostering concurrent collaboration for parameter processing and determination multidimensionally across diverse functional domains, such as the market-driven, user-driven, aesthetic-driven and engineering-driven domains. Following the two collaboration forms *between* units and *within* units identified in the representative FFE scenario, two mechanisms, Mechanism 2.1 and 2.2, were devised.

2.1) Mechanism 2.1 for Concurrent Collaboration *between* Toolkits

Mechanism 2.1 for activating concurrent collaboration, shown in **Figure 6**, aims to reflect simultaneous collaborative works *between* performance method units of different activity units (representing the functional domains) which exist in a *parallel* arrangement identified in the representative FFE scenario. The toolkit structure for this concurrent collaboration was constructed with the following three steps.

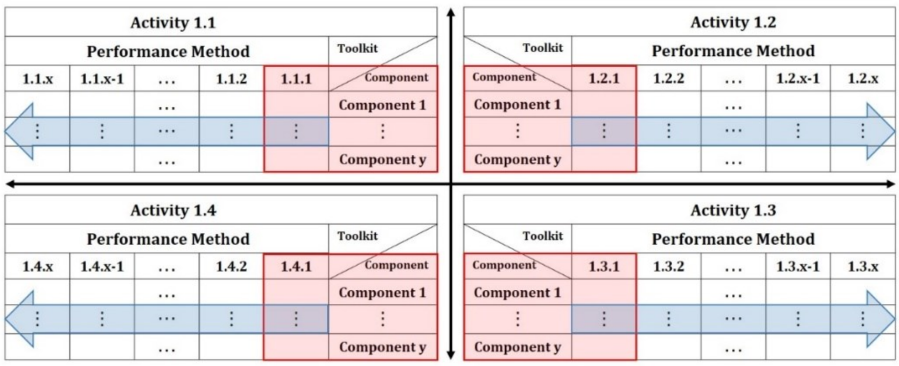

Figure 6. Mechanism 2.1 for concurrent collaboration ***between*** *t*oolkits

Firstly, activity units where toolkits were connected for contextual performance between performance method units by applying Mechanism 1 were laid out in a clockwise direction, in quadrants. Secondly, these activity units interlocked with each other with toolkits playing a common (similar) role as the centre (shown in the red blocks). Thirdly, in each activity unit placed in the quadrants, the x axis consists of the remaining toolkits stretching out with those four centric toolkits as the centre while the y axis was structured on a component basis.

With this structure, while parameters are produced in succession from toolkits for performance method units in one activity unit (one functional domain), other parameters in toolkits for other performance method units of the remaining three activity units (the remaining three functional domains), placed in the same latitude of the x axis, can be simultaneously considered (shown in the blue arrows). This concurrent collaboration is possible not only *in* components but also *between* components, given their nature where adjacent components have a strong relationship.

2.2) Mechanism 2.2 for Concurrent Collaboration *within* Toolkits

Distinct from Mechanism 2.1, Mechanism 2.2, shown in **Figure 7**, aims to reflect simultaneous collaborative works *within* performance units of different activity units which exist in a *sequential* arrangement, identified in the representative FFE scenario. The toolkit structure for this concurrent collaboration was constructed with the following two steps.

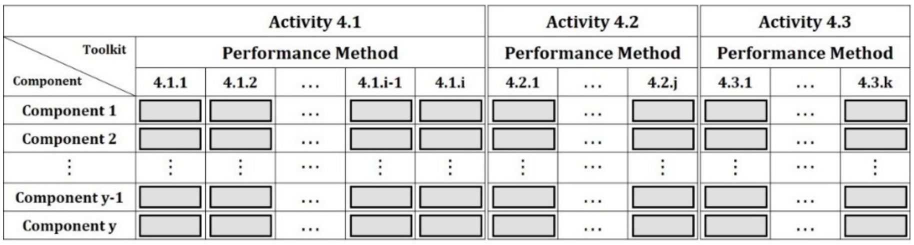

Figure 7. Mechanism 2.2 for concurrent collaboration ***within*** toolkits

Firstly, activity units where toolkits for performance method units were connected for contextual performance by applying Mechanism 1 were placed in phases on the x axis instead of arranged in quadrants. Secondly, the y axis was structured on a component basis.

With this structure, parameters can be produced in each toolkit, involving the viewpoints of the multiple functional domains (shown in the black blocks). Also, those parameters can be obtained, with consideration of not only individual components but their relationships.

3.3.2 Concept Generation

The model developed with the model building mechanisms above was converted into a schematic chart wherein the model structure is depicted. The chart was expressed with a mathematical formula which indicates an FFE execution concept. The conceptual method for producing the Concept were referenced from studies on 'Axiomatic Design Theory' [56, 57] which provides mathematical theories for different sequential steps of design activities.

4 Data-driven FFE Model Development and FFE Execution Concept Inference

This section addresses the data-driven FFE model which the representative FFE scenario was embodied with the three model building mechanisms. This study also handles the FFE execution concept and associated mathematical reasoning behind the model structure and its operating mechanism. The model and concept have a structure consisting of four main FFE task units as follows.

4.1 Task 1: Opportunity Identification Task

The purpose of Task 1 for opportunity identification is to scrutinise the target product on a component basis through research into four functional domains: 1) market-driven domain, 2) user-driven domain, 3) aesthetical-driven domain, and 4) engineering-driven domain. In the representative FFE scenario, four research activity units conducted from the viewpoint of those four functional domains were revealed, and these units operated in parallel. Diverse performance method units which have the contextual performance relationship within each activity unit were identified and these units required a strong possibility for concurrent collaboration beyond each activity border.

4.1.1 Toolkits for Contextual Performance in Task 1: Opportunity Identification Task

As shown in **Figures 8** to **12**, by applying Mechanism 1, each activity unit was structured with toolkits sequentially arranged considering the contextual performance relationship between performance method units as defined in the representative FFE scenario.

Table 3. Quotes of contextual performance in Activity 1.1 (Part 1) for market-driven research

Participants	Quotes
P02	"… The main purpose of the market research activity can be divided into two dimensions. The former dimension is for the user and market segmentation. The latter is for …"
P16	"… firstly, we investigate user groups in detail for expecting target markets …"
P03	"… In the first step, we understand user types. We call it the stakeholder analysis. This involves 'Gender', 'Age', 'Region', 'Job' and 'Income' …"
P03	"… To select the possible market for those user types, we need to find out various indirect factors affecting the possible market first. The tool, 'BEPSTELVE" is named by the first letter of each factor. 'B' is for business, 'E' is for Economy, 'P' is for politics, 'S' is …"
P29	"… Depending upon different layers of users and analysing various indirect factors affecting the possible market, actual market status can be defined using some tools such as SWOT, PDP, and so on …"
P18	"… SWOT analysis is defining direct factors affecting the market status for expecting the actual target market … this leads which market is proper for the product to be positioned. According to the product positioning, the distribution and promotion method can be different … we call it PDP analysis …"

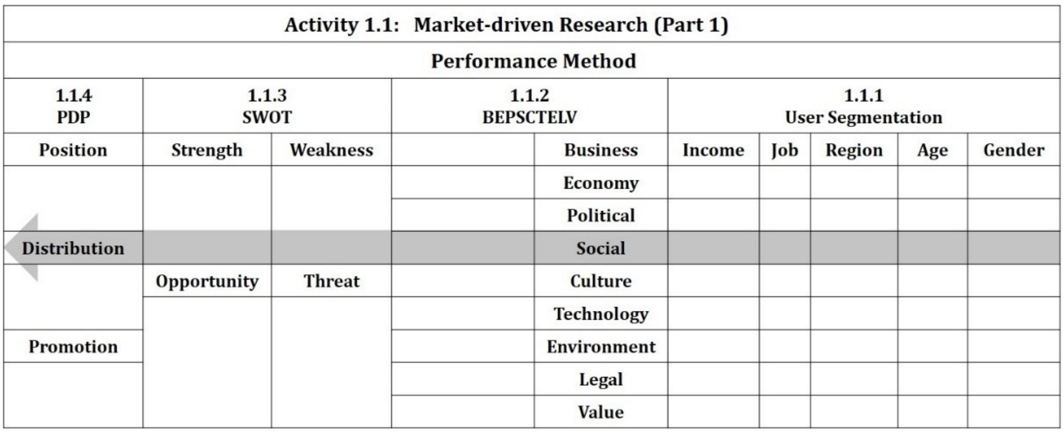

Figure 8. Contextual performance in Activity 1.1 (Part 1) for market-driven research

Firstly, the market-driven research activity (Activity 1.1) can be divided into two parts. In the first part (**Table 3** and **Figure 8**), relating to target users and markets, full details of the user types who will use the target product can be segmented (Performance Method 1.1.1), and then based on parameters produced in the user segmentation toolkit, the indirect and direct factors affecting the possible target market in which those user types and the target product are situated can be investigated (Performance Methods 1.1.2 and 1.2.3). Based on this possible market,

market positioning-distribution-promotion strategies can be established, to estimate an actual target market (Performance Method 1.1.4).

In the second part (**Table 4** and **Figure 9**), relating to financial aspects, an investment cost can be estimated first, an estimation which will adjust the budget (Performance Method 1.1.5). A product price can then be determined, considering the margin (Performance Method 1.1.6). Based on the cost and price, profits can be forecast, on a monthly and annual basis (Performance Method 1.1.7).

Table 4. Quotes of contextual performance in Activity 1.1 (Part 2) for market-driven research

Participants	Quotes
P02	"… The main purpose of the market research activity can be divided into two dimensions … The latter is for the financial aspect, cost, price-and profit …"
P22	"… Depending on the investment cost, the price of product can be estimated. To make a profit, the price should be higher than the cost …"
P37	"… the budget influences on investment cost, and this affect the product price defining and profit forecasting … profit can be estimated on a monthly and annual basis"
P31	"… the investment cost estimation includes direct and indirect cost and target cost …"
P29	"… the pricing involves calculating the expected margin, selling price and actual margin …"

Activity 1.1: Market-driven Research (Part 2)								
Performance Method								**Toolkit** / **Component**
1.1.7 Profit Forecasting		**1.1.6 Product Price Estimation**			**1.1.5 Investment Cost Estimation**			
Annual	**Month**	**Actual Margin**	**Selling Price**	**Expected Margin**	**Target Cost**	**Indirect Cost**	**Direct Cost**	
								Component 1
⋮	⋮	⋮	⋮				⋮	⋮
								Component n
								Whole Product

Figure 9. Contextual performance in Activity 1.1 (Part 2) for market-driven research

Secondly, the user-driven research activity (Activity 1.2) aims to grasp user behaviours when the defined target users use the target product in a given environment. As shown in **Table 5** and **Figure 10**, This activity can begin by investigating the order in which target users operate the target product (Performance Method 1.2.1). Each step of the product usage process can generate a user touch-point (Performance Method 1.2.2), involving the interaction system between users and the product (Performance Method 1.2.3). In the interaction system, users' actions come from the product usage process are inputs, touch-points are mediators, and those touch-points' responses are outputs. After determining what form the interaction takes, we can define product usage functions more explicitly (Performance Method 1.2.4), and then see how users make use of the target product in a given set of environments (Performance Method 1.2.5). This leads to a usability analysis, looking at the product's ergonomics and human factors (Performance Method 1.2.6). Encompassing all the parameters produced by using the toolkits above, a user-scenario – an overall scene where target users display particular behaviour patterns in the given environment – can be envisaged (Performance Method 1.2.7).

Table 5. Quotes of contextual performance in Activity 1.2 for user-driven research

Participants	Quotes
P23	"… this work is figure out user behaviours when the target users use the target product in an associated environment …"
P01	"… in the user-lead research, yes, the order of the operation can be the starting point …"
P32	"… in the examination of each operation sequence, each user touch point, as each component of the product, can be produced …"
P14	"… each user touch point can take each associated interaction system …"
P06	"… the interaction system normally consists of three parts, user's actions as inputs, user touch points as mediator, and product's responses as outputs …"
P21	"… by understanding the interaction system, we can define product functions for users …"
P19	"… an understanding of how users are using the given environments with the given functions draws a calculation of ergonomics for each user touch point …"
P29	"… This is to make an overall scene of blueprint of how users are using products in a certain environment with their particular behaviour patterns …This method can be final and ultimate work in the user-oriented research …"

Activity 1.2: User-driven Research								
Performance Method								
1.2.1 Product Usage Process	1.2.2 User Touch Point	1.2.3 Interaction System			1.2.4 Product Usage Function	1.2.5 User Environment	1.2.6 Usability Ergonomics	1.2.7 User Scenario
		Input	Mediator	Output				
	Component 1							
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	
	Component n							
	Whole Product							

Figure 10. Contextual performance in Activity 1.2 for user-driven research

Thirdly, the aesthetic-driven research activity (Activity 1.3) aims to increase the aesthetic value of the target product and infuse symbol functions into the product. As seen in **Table 6** and **Figure 11**, this module starts to explore the possible shapes for the target product, both in its entirety and for its component parts (Performance Method 1.3.1). Next, features such as appropriate colours and materials that best match with those forms can be suggested (Performance Methods 1.3.2 and 1.3.3). Then, the finishing specifications can be examined to increase the degree of completion of the target product's appearance (Performance Method 1.3.4). Subsequently, the symbology of the forms, colours, materials, and even finishing specifications are described as relevant to the product (Performance Method 1.3.5). Lastly, by reflecting all the parameters of the above five product exterior elements, an image map can be developed to conceptualise the overall initial image of the product (Performance Method 1.3.6).

Table 6. Quotes of contextual performance in Activity 1.3 for aesthetic-driven research

Participants	Quotes
P03	"… opportunities can also be attained from design aspect. It deals with exterior issues related to how to increase aesthetic value, external quality of the product …"
P09	"… the entire product's, as well as, for each component, the form, the shape can be estimated … the form follows functions"
P22	"… considering the form of the product, the relevant colour and material is determined …"
P33	"… colour, material, finishes, CMF, can be worked as a group or worked individually …"
P13	"… shape and colour are the design elements users feel by their eye and material is the element users feel mainly by their hand … Each element can give a symbolic emotion, for example …"
P17	"… Finishes is related to the completion of the product' exterior …"
P24	"… encompassing all the elements, we can finally draw product's image and semantic map ..."

Activity 1.3: Aesthetic-driven Research						
Toolkit / Component	**Performance Method**					
	1.3.1 Shape	**1.3.2 Colour**	**1.3.3 Material**	**1.3.4 Symbol**	**1.3.5 Finishes**	**1.3.6 Image Map**
Component 1						
⋮	⋮	⋮	⋮	⋮	⋮	
Component n						
Whole Product						

Figure 11. Contextual performance in Activity 1.3 for aesthetic-driven research

Fourthly, the engineering-driven research activity (Activity 1.4) can play a pivotal role in enabling the technical operation of the target product. As shown in **Table 7** and **Figure 12**, this activity can start by defining the technical roles of the technical compositions that make up the target product (Performance Method 1.4.1). With an understanding of the technical roles and their relationships, each composition can be deployed, forming the functional structure of the product (Performance Method 1.4.2). By grasping the processing systems of each composition and their systemic relationships in the wider functional structure, the system structure can be devised, with consideration of how the product can be operated technically (Performance Method 1.4.3). Then, technical parameters can be calculated to see how energies, materials and signals are transferred through those processing systems and their systemic connections (Performance Method 1.4.4). Based on these parameters, operational mechanisms for not only the product as a whole but also its various compositions can be understood explicitly (Performance Method 1.4.5). These operational mechanisms, along with the technical parameters, enable us to estimate the possible range of technical dimensions (Performance Method 1.4.6). Lastly, by considering the parameters of previous implementations, either selectively or comprehensively, technologies required to operate the product and its compositions can be examined (Performance Method 1.4.7).

Table 7. Quotes of contextual performance in Activity 1.4 for engineering-driven research

Participants	Quotes
P18	"… the engineering, technology-led research is to enable the technical operation of the target product ,,,"
P01	"… On the back of the product's function which provide to users, technical function exists. In the first step, technical functions which serve as enabling product's functions to be operated can be defined on a component basis…"
P36	"… After defining technical functions in this manner, based on the flow between those functions, we can draw a functional inner structure …"
P18	"… Each function in the function structure has each processing system to operate functions. The connection of the system leads to producing technical system structure of the product …"
P14	"… in each block of the system structure, we can quite accurately estimate which and how technical parameters are generated …"
P17	"… Based on each part's system flow, we can know relevant technical parameters in each part, so that specifically understand each operation mechanism, working principles …"
P04	"… After defining the working mechanisms, the range of technical dimensions for the product or its parts can be estimated …"
P29	"… research finally involves identifying which technologies are required for the product …"

Activity 1.4: Engineering-driven Research								
Performance Method								Toolkit / Component
1.4.7 Required Tech	1.4.6 Technical Dimension	1.4.5 Working Principle	1.4.4 Technical Parameter Output	1.4.4 Technical Parameter Input	1.4.3 System Structure	1.4.2 Function Structure	1.4.1 Technical Function	
								Component 1
⋮	⋮	⋮	⋮				⋮	⋮
								Component n
								Whole Product

Figure 12. Contextual performance in Activity 1.4 for engineering-driven research

Due to this phased structure, once parameters are generated in the first toolkit of each research activity unit, the remaining parameters from the second to the final toolkit can be built up consecutively for each component as well as for the entire product.

4.1.2 Toolkits for Concurrent Collaboration in Task 1: Opportunity Identification Task

As shown in **Figure 13**, by applying Mechanism 2.1, four activity units built above were laid out in the clockwise direction in quadrants, considering the parallel relationship between each activity unit as defined in the representative FFE scenario. This structure can contribute to facilitating concurrent collaboration between toolkits of four different activity units.

Concurrent collaboration can be activated with the following four steps. Firstly (1), the target user types and the target market for the target product can be segmented in the market-driven research activity (Activity 1.1–Part 1). Next (2), in quadrant 2, considering phased-motions in which the users use the product in the market, user touch-points generated in each step of the product usage process can be investigated, which leads to defining product components from the user-driven research perspective (Activity 1.2). Then (3), based on this fiducial line ('BY column'), product components from the viewpoints of the aesthetic-driven, engineering-driven and market-driven research activities can be defined, in quadrants 3, 4 and 1 respectively: 1) In quadrant 3 (Activity 1.3), forms of components are explored considering how the users perceive the user touch-points morphologically, 2) In quadrant 4 (Activity 1.4), technical functions of components are studied in that there are those technical components on the backs of the user touch-points, and 3) In quadrant 1 (Activity 1.1–Part 2), investment costs of those technical components are estimated. These initial four performances in each activity unit have in common the role of initiating component-based performance. Fourthly (4), once product components are defined in each activity unit, the calculation of parameters in the remaining toolkits can be implemented consecutively within each activity unit in the way mentioned in the previous section and also executed concurrently in all activity units. While parameters are produced in succession for contextual performance from the toolkits of one activity unit, other parameters in the toolkits of the remaining three activity units, placed in the same latitude of the x axis, can be simultaneously considered. In calculating the parameters from each toolkit, other parameters obtained in the toolkits of different activity units representing four functional domains can be considered concurrently within the same component.

Table 8. Quotes of concurrent collaboration in Task 1 for opportunity identification

Participants	Quotes
P22	"…on the back of each single user touch-point, there are several technical components, and their technical function structures can be constructed differently by considering arrangements of those user touch-points …"
P13	"… by considering each interaction system generated in each user touch-point, proper shape, colour and material of the product and its components can be estimated …"
P33	"… interaction system and product usage functions can affect the components' form, CMF, technical working principles, technical dimensions …"
P05	"…considering those interaction systems, technical parameters produced from systemic relationships between those interactions can be calculated and thereby proper technical working principles and technical dimensions can also be devised accordingly …"
P19	"… such as usability and ergonomics affect the calculation of technical dimensions …"
P34	"… materials and new technologies involved in the product or its component, the investment cost can be defined and product pricing can be done accordingly …"
P01	"… according to which functions the product takes, the investment cost can be adjusted …"
P08	"… when drawing user stories, we can imagine an overall image map of the product …"
P24	"… according to the material scope estimated, the materials' technical properties can be different … sometimes we can simultaneously consider the possible form, material affecting the possible form, and corresponding technical property …"
P31	"… of course, the arrangement of user touch points directly influences on the technical function structure … but, sometimes, we need to consider the product usage process together with …"

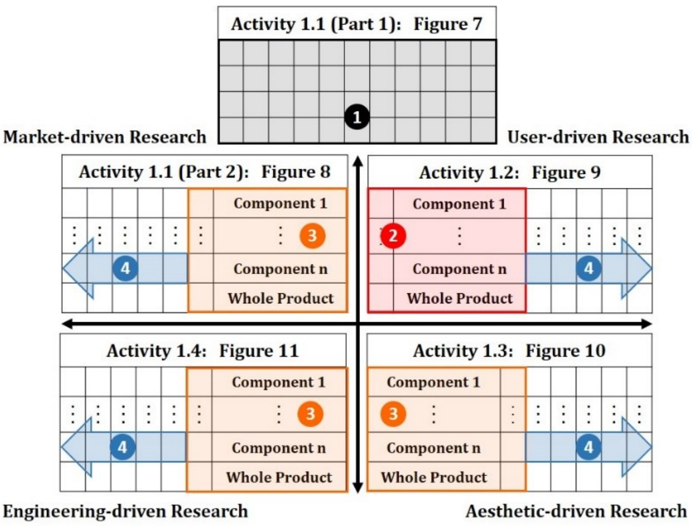

Figure 13. Concurrent collaboration in Task 1 for opportunity identification

For instance, in the development of an electrical wheelchair, different usage functions were required for different environments, such as stairs, slopes, and gates at mass transit railway stations. Functionality for these environments demands different technical operational mechanisms for the wheels (and the control panel). Those parameters produced can be for users handicapped in their legs only. For users handicapped in both legs and arms, the working principles and technical dimensions must be modified and forms more appropriate for quadriplegics can be proposed. In this way, user segmentation, user touch-point identification, product usage function definition, user environment study, operation mechanism design, technical dimension calculation, and the shape selection can be simultaneously conducted.

In another example, when developing an amphibious drone, the upper part of the body container is generally above the surface of the water, while the bottom part is submerged. These two environments will require different materials which have different technical properties. This changes the investment cost. In this way, user environment study, material selection, the calculation of technical properties, and budget adjustment can be concurrently conducted.

With this structure, it makes possible that more abundant and accurate individual parameters are generated, through contextual and concurrent operations from the viewpoint of either various performance methods or research domains.

4.1.3 Execution Concept for Task 1: Opportunity Identification

Table 9 gives a schematic chart for Task 1.

Table 9. Schematic chart of Task 1 for opportunity identification

o_k^m = Market-driven Research		
o_1^m	Parameter set 1	Component 1
⋮	⋮	⋮
o_n^m	Parameter set n	Component n

		User-driven Research = o_k^u
Component 1	Parameter set 1	o_1^u
⋮	⋮	⋮
Component n	Parameter set n	o_n^u

o_k^e = Engineering-driven Research

Aesthetic-driven Research = o_k^a

o_1^e	Parameter set 1	Component 1
⋮	⋮	⋮
o_n^e	Parameter set n	Component n

Component 1	Parameter set 1	o_1^a
⋮	⋮	⋮
Component n	Parameter set n	o_n^a

o = opportunity, m = market-driven, u = user-driven, a = aesthetic-driven, e = engineering-driven,
k = component No., 1≤ $k \leq n$

This schematic chart can be expressed as the following equation (1):

$$\boldsymbol{O_k} = \begin{vmatrix} o_1^m + o_1^u + o_1^a + o_1^e \\ o_2^m + o_2^u + o_2^a + o_2^e \\ o_3^m + o_3^u + o_3^a + o_3^e \\ \vdots \\ o_n^m + o_n^u + o_n^a + o_n^e \end{vmatrix} = \begin{vmatrix} O_1 \\ O_2 \\ O_3 \\ \vdots \\ O_n \end{vmatrix} = \begin{vmatrix} Opportunity\ Parmeter\ set\ for\ component\ 1 \\ Opportunity\ \ Parmeter\ set\ for\ component\ 2 \\ Opportunity\ \ Parmeter\ set\ for\ component\ 3 \\ \vdots \\ Opportunity\ Parmeter\ set\ for\ component\ n \end{vmatrix}$$

$$\boldsymbol{O_k} = o_k^m + o_k^u + o_k^a + o_k^t \text{ (1)}$$

The equation indicates that opportunities are NPD-related parameter sets scrutinised on a component basis from the market-driven, user-driven, aesthetic-driven, and engineering-driven research activities.

4.2 Task 2: Idea Generation Task

Task 2 for idea generation aims to devise ideas in the form of actionable methods/solutions to materialise the parameters produced in the opportunity identification task (Task 1). In the representative FFE scenario, as with Task 1, the activity units of four functional domains were observed to exist and possibilities for concurrent collaboration between these units were revealed, in a parallel relationship. In the case of performance method units that make up each activity unit, unlike Task 1 in which different kinds of performance method units were revealed to exist in each activity unit, a common pattern was extracted from the different performance methods provided by each interviewee. Based on the common pattern, a representative ideation processing method was deduced, one that could be applied to all activities.

4.2.1 Toolkits for Contextual Performance in Task 2: Idea Generation Task

As shown in **Table 10** and **Figure 14**, activity units were built based on the concept of mapping out 'How' (ideas as actionable methods/solutions) for 'What' (opportunities) based on 'Why' (supportive reasons and rational evidence). This led to the four activity units representing the ideation activities of the four functional domains being arranged as an extension to each associated functional domain's research activity unit in Task 1. The set of toolkits in Task 2 and the set of toolkits in Task 1 can interlock with each other: the initial toolkit in each activity unit of Task 2 is interlocked with the final toolkit in each corresponding activity unit of Task 1 on the same latitude of the horizontal axis (on the component basis).

Table 10. Quotes of contextual performance in Task 2 for idea generation

Participants	Quotes
P07	"… idea generation is for us to come up with specific methods to embody each opportunity explored in opportunity identification of the new business discovering stage …"
P19	"… idea generation is to devise proper methods, as workable solutions, required to actually materialise elements discovered in the previous work, opportunity identification …"
P34	"… based on the rational evidence, 'Why', devising actionable methods, 'How', for opportunities, 'What', is the ideation work …"
P09	"… a set of opportunities for each component can go with a set of ideas for each component …"
P25	"… in the series, there is a step of what to do to realise opportunities, a step of what to know before doing that step, and a step of what to do more specifically for these two steps …"
P22	"… When we get our teeth into ideas deeply, we always try to keep "why we need the ideas …"
P14	"… how we do … in what specific ways might we reflect those opportunities in the product … how might we practically reflect those opportunities in the product … what are supportive reasons and rationale evidence? … how might we more specify those actions …"
P16	"… the initial ideas and associated supportive reasons can be break down into more specific ideas and their supportive reasons …"
P05	"… we divergently specify discovered opportunities, producing possible solutions along with supportive reasons Then, we prioritise them at different levels from the feasibility aspect …"
P13	"… for the feasibility check, we can use traffic signal's colour, such as red representing …"

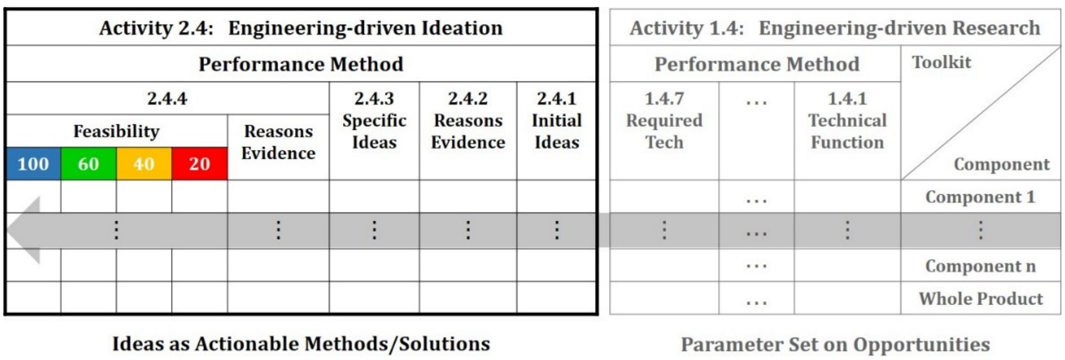

Figure 14. Contextual performance in Task 2 for idea generation

In Task 2, the purpose of the first toolkit in each ideation activity unit is to come up with initial ideas to materialise the set of parameters placed on the same horizontal line in each corresponding research activity unit of Task 1.

For instance, the set of opportunity parameters for a medical cart's handle, in the user-driven research activity (Activity 1.2) of Task 1, can be as follows: 1) doctors and nurses grab and push (push) the handle with one or both hands when moving the device (in Performance Methods 1.2.2 and 1.2.3 for the user touch-point and interaction system study), 2) the handle is usually exposed to open space, but users sometimes must 'interact' with doors or walls when the device is moving or stationary (in Performance Method 1.2.5 for the user environment investigation), 3) the handle's diameter should be comfortably within the width of the palm of a wide range of user (in Performance Method 1.2.6 for the ergonomics study). Based on this set of opportunity parameters, various handle types can be devised, e.g. foldable and non-foldable, detachable and non-detachable, of the '⊏', '⊢', and '⊨' morphological forms.

In another example of a baby layettes steriliser, in the aesthetic-driven research activity (Activity 1.3), the set of opportunity parameters for the device's body container can be as follows: square shaped, silver-coloured metal for the container which does not require an assembly line to produce, and whose exterior elements convey a hygiene symbol in some way. Therefore, based on this set of parameters, initial ideas can be explored in terms of variants of the square shape, silver colour, metallic material, considering non-parting lines and semiotics indicative of sanitation. Possible shapes include rectangle-, rhombus-, parallelogram- or trapezium-shaped containers. For colour, several silver colours were nominated, using international colour codes. A number of metals, including various alloys of steel, aluminium, chromium, etc., can also be investigated, again using international codes, this time for materials. Besides, possible OEMs/Vendors which can provide these exterior elements can be examined.

The purpose of the second toolkit is to investigate supportive reasons and rational evidence for the initial ideas. The third and fourth toolkits aim not only to transform the initial ideas into further specific actionable methods/solutions but also to analyse their features, strengths, and weaknesses, for a feasibility check.

With this phased structure, each set of opportunity parameters obtained in Task 1 can be advanced into something more concrete, as actionable idea parameters, for each component as well as for the whole product, in Task 2.

4.2.2 Toolkits for Concurrent Collaboration in Task 2: Idea Generation Task

As seen in **Figure 15**, arranging the four ideation activity units as an extension to each associated research activity unit led to the placing of those four ideation activity units in quadrants as if adopting Mechanism 2.1. With the placement of activity units in quadrants, representing ideation work in the four functional domains, the method to foster concurrent collaboration in Task 2 is the same as that in Task 1. Ideas and their supporting reasons/rational evidence in each toolkit of one activity unit can be developed with simultaneous consideration of other ideas and associated reasons/evidence devised in other toolkits of the three remaining activity units. This collaborative system can also operate within a component as well as between different components, as with Task 1.

Table 11. Quotes of concurrent collaboration in Task 2 for idea generation

Participants	Quotes
P28	"… when coming up with ideas, we should simultaneously consider the viewpoints of four functional domains previously mentioned … we can devise ideas on a component basis …"
P31	"… idea generation in a certain functional domain affect idea generation in the remaining function domains …"
P06	"… in selecting colour and material codes from their scopes estimated in opportunity identification, we can search possible vendors or OEMs to manufacture them to appropriate more accurate budget …"
P13	"… considering ideas related to the product usage functions, environments, and ergonomics, we can select ideas for shape, CMF for the whole product as well as its component parts …"
P13	"… further, considering ideas related to the product usage functions, environments, and ergonomics, we can select ideas for technical working principles and technical dimensions for the whole product as well as its component parts …"
P38	"… when producing ideas for product functions and usability, ideas for technical working mechanisms can be more explicit and technical dimensions can be defined accordingly …"

P27	"… according to ideas on required technologies, ideas for investment cost can be different …"
P14	"… ideas on user touch points' arrangement affect ideas on technical function and system structure …"

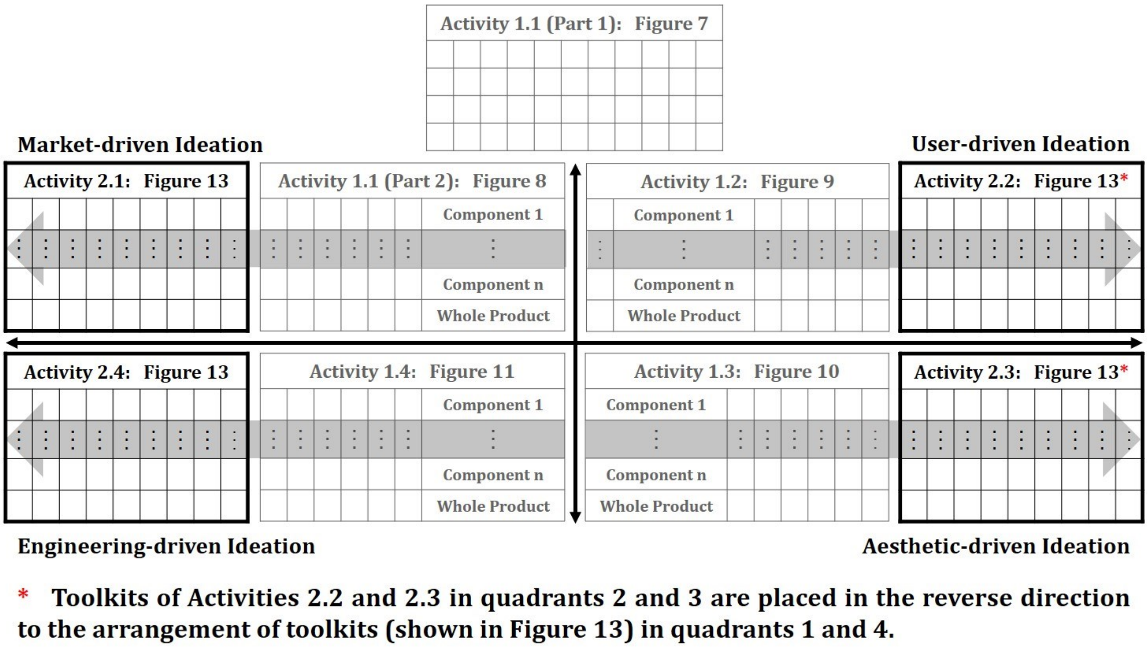

Figure 15. Concurrent collaboration in Task 2 for idea generation

4.2.3 Execution Concept for Task 2: Idea Generation

Table 12 gives a schematic for Task 2.

Table 12. Schematic chart of Task 2 for idea generation

$\boldsymbol{i_k^m}$ = **Market-driven Ideation**		
i_1^m	Parameter set 1	Component 1
⋮	⋮	⋮
i_n^m	Parameter set n	Component n

		User-driven Ideation = $\boldsymbol{i_k^u}$
Component 1	Parameter set 1	i_1^u
⋮	⋮	⋮
Component n	Parameter set n	i_k^u

$\boldsymbol{i_k^e}$ = **Engineering-driven Ideation**		
i_1^e	Parameter set 1	Component 1
⋮	⋮	⋮
i_n^e	Parameter set n	Component n

		Aesthetic-driven Ideation = $\boldsymbol{i_k^a}$
Component 1	Parameter set 1	i_1^a
⋮	⋮	⋮
Component n	Parameter set n	i_n^a

i = idea, m = market-driven, u = user-driven, a = aesthetic-driven, e = engineering-driven
k = component No., 1≤ k ≤ n

This schematic chart can be represented as the following equation (2):

$$\boldsymbol{I_k} = \begin{vmatrix} i_1^m + i_1^u + i_1^a + i_1^e \\ i_2^m + i_2^u + i_2^a + i_2^e \\ i_3^m + i_3^u + i_3^a + i_3^e \\ \vdots \\ i_n^m + i_n^u + i_n^a + i_n^e \end{vmatrix} = \begin{vmatrix} I_1 \\ I_2 \\ I_3 \\ \vdots \\ I_n \end{vmatrix} = \begin{vmatrix} Realisation\ Method\ Parameter\ set\ for\ Component\ 1 \\ Realisation\ Method\ Parameter\ set\ \ for\ Component\ 2 \\ Realisation\ Method\ Parameter\ set\ \ for\ Component\ 3 \\ \vdots \\ Realisation\ Method\ Parameter\ set\ for\ Component\ n \end{vmatrix}$$

$$\boldsymbol{I_k} = i_k^m + i_k^u + i_k^a + i_k^t \ (2)$$

This equation represents that ideas are actionable realisation method parameter sets devised on a component basis from the market-driven, user-driven, aesthetic-driven, and engineering-driven ideation activities.

4.3 Task 3: Requirements List Task

Task 3, which concerns the requirements list, aims to draw up the parameters obtained in the opportunity identification (Task 1) and idea generation (Task 2) tasks. In the representative FFE scenario, two activity units, for listing up requirements for components and the entire product respectively, were revealed to exist and these units had a sequential relationship instead of the parallel relationship. Performance method units which have the contextual performance relationship within each activity unit were observed to exist and these units demanded concurrent collaboration within each performance method unit instead of between units.

4.3.1 Toolkits for Contextual Performance in Task 3: Requirements List Task

Task 3 was structured with two activity units in a phased relationship.

Table 13. Quotes of contextual performance in Task 3 for requirements list

Participants	Quotes
P37	"… but, it will be a huge fault. If we do not manage requirements of the product development in the early stage, the concept design can have imperfect since functional and technical specifications are less reflected in the concepts, so testing prototypes will be less meaningful …"
P03	"… so, requirements list does mean a list of 'Specs' … we usually make the list of 'Specs' on the basis of discovered opportunities and devised ideas … including product features such as user and technical functions, required technologies, design elements, market and cost …"
P06	"… when making the requirements list, as a 'Mini-map' of the product development …"
P16	"… drawing up the product specification is a kind of developing an 'Initial Overall Map' consisting of a parameter set of opportunities and ideas … on a component basis…"
P22	"… the requirements list should include whether each requirement for each component is feasible essentially and selectively ..."
P27	"… product specification for each component is divided into 'Must be Criteria'; essential element and 'Should be Criteria'; selective element …"

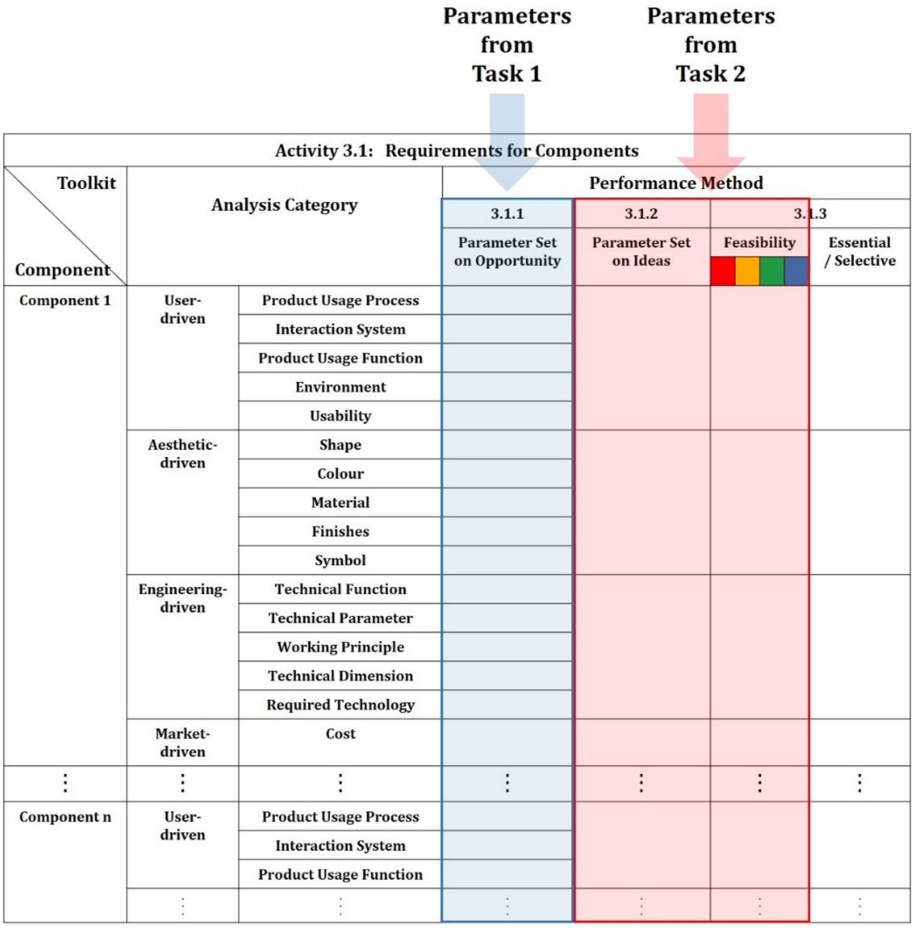

Figure 16. Requirements for components in Task 3

The first activity unit (Activity 3.1) is for building product specification on a component basis, consisting of parameters from the opportunity discovery and ideation tasks (Tasks 1 and 2). In order to functionally embody this concept in the structure, this activity unit was structured as an extension of the previous two tasks, as shown in **Table 13** and **Figure 16**. This allows this activity unit to interlock with the previous two tasks on a component basis, segmented into the four functional domains, on the vertical axis. The horizontal axis was structured with three toolkits for performance methods, in the following order: 1) Performance Method 1.3.1: sets of opportunity parameters obtained from Task 1, 2) Performance Method 1.3.2: sets of idea parameters gained from Task 2, and 3) Performance Method 1.3.3: a degree of feasibility attained from Task 2. With this structure, requirements consisting of opportunities and ideas to materialise these opportunities, on a product component basis, can be grasped systematically.

The second activity unit (Activity 3.2) aims to summarise the entire target product by building up the condensed set of requirements. As shown in Figures 8 to 12, each activity unit in Task 1 has each particular toolkit which encompassed most of the parameters produced in each activity unit. As seen in **Figure 17**, Activity 3.2 was structured with these toolkits: 1) Market-driven research (Activity 1.1): the overall development cost and price estimation and profit forecasting, 2) User-driven research (Activity 1.2): the user scenario mapping, 3) Aesthetic-driven research (Activity 1.3): the image map building, and 4) Engineering-driven research (Activity 1.4): the system structure development. Most of the contents of these parts are expressed primarily with image in the form of schematics, accompanied by brief explanations.

Activity 3.2: Requirements for Product	
Analysis Category	**Performance Method**
User-driven	**User Scenario**
Aesthetic-driven	**Image Map**
Engineering-driven	**System Structure**
Market-driven	**Cost-Price-Profit**

Figure 17. Requirements for the entire product in Task 3

4.3.2 Toolkits for Concurrent Collaboration in Task 3: Requirements List Task

Table 14. Quotes of concurrent collaboration in Task 3 for requirements list

Participants	Quotes
P14	"… by so doing this, performers who come from different functional domains can do inter-checking and cross-checking the requirements of the product simultaneously …"
P07	"… one or two pages of requirements list allow concurrent inter-checking and cross-checking requirements of the target product from the viewpoint of the four functional domains …"
P31	"… the requirements list should be drawn up, enabling the simultaneous checking of requirements by performers involved in those four functional domains' works …"

Unlike Tasks 1 and 2, which were arranged in quadrants and in parallel for concurrent collaboration between performance method units of different activity units, activity units in

Task 3 were sequentially placed by applying Mechanism 2.2, for concurrent collaboration within performance method units of activity units. As seen in **Table 14** and **Figure 16**, by dividing each component into the four functional domains, it is possible to allow concurrent inter-checking as well as cross-checking of requirements from the viewpoint of those functional domains. Furthermore, by arranging requirements in the order that the relevant product components come into play, the relationship between the requirements of adjacent components can be achieved more functionally and with greater ease.

4.3.3 Execution Concept for Task 3: Requirements List

Table 15 shows a chart in which the structure of Activity 3.1 in Task 3 for listing requirements of components is schematised.

Table 15. Schematic chart of Activity 3.1 of Task 3 for requirements of components

Component	Opportunity = $\boldsymbol{O_k}$	Idea = $\boldsymbol{I_k}$	Requirement = $\boldsymbol{R_k}$
Component 1	$o_1^m + o_1^u + o_1^a + o_1^e = O_1$	$i_1^m + i_1^u + i_1^a + i_1^e = I_1$	$O_1 \, x \, I_1 = R_1$
⋮	⋮	⋮	⋮
Component n	$o_n^m + o_n^u + o_n^a + o_n^e = O_n$	$i_n^m + i_n^u + i_n^a + i_n^e = I_n$	$O_n \text{ x } I_n = R_n$

o = opportunity, i = idea, m = market-driven, u = user-driven, a = aesthetic-driven, e = engineering-driven
k = component No., $1 \leq k \leq n$

The core aim of Task 3 is to enumerate product specification parameters. The execution mechanism for this rests in the requirements for each component, which consists of a combination of opportunity and idea parameters. The term *combination* here refers not to a simple physical integration but an inherent fusion for building a form of requirements. Therefore, an equation (3) for the requirements of each component can be expressed as follows:

$$\boldsymbol{R_k} = O_k \times I_k \text{ (3)}$$

Table 7. Schematic chart of Activity 3.2 of Task 3 for requirements of product

Product	Opportunity = $\boldsymbol{O_k}$	Idea = $\boldsymbol{I_k}$	Requirement = $\boldsymbol{R_k}$
Component 1 + ⋮ + Component n	$O_k = \begin{vmatrix} O_1 \\ \vdots \\ O_n \end{vmatrix}$ $O_k = \begin{vmatrix} O_1 & O_2 & \cdots & O_n \end{vmatrix}$	$I_k = \begin{vmatrix} I_1 \\ \vdots \\ I_n \end{vmatrix}$ $I_k = \begin{vmatrix} I_1 & I_2 & \cdots & I_n \end{vmatrix}$	$(O_1 \text{ x } I_1)$ + ⋮ + $(O_n \text{ x } I_n)$

Also, as shown in **Table 7**, the overall requirements for the product can be formed by adding up the requirements of each component, which can be depicted with the following equation (4):

$$|o_1^m + o_1^u + o_1^a + o_1^e \quad \cdots \quad o_n^m + o_n^u + o_n^a + o_n^e| \times \begin{vmatrix} i_1^m + i_1^u + i_1^a + i_1^e \\ i_2^m + i_2^u + i_2^a + i_2^e \\ \vdots \\ i_n^m + i_n^u + i_n^a + i_n^e \end{vmatrix}$$

$$= |O_1 \quad \cdots \quad O_k| \times \begin{vmatrix} I_1 \\ \vdots \\ I_n \end{vmatrix}$$

$$= (O_1 \text{ x } I_1) + \ ... + (O_n \text{ x } I_n) \ = \ \sum_{k=1}^{n} O_k \times I_k$$

$$= \ R_1 \ + \ ... \ + \ R_k \ = \ \sum_{k=1}^{n} R_k \ (4)$$

This equation indicates that the overall requirements for the target product are to sum up requirements formed by the combination of the opportunity and realisation method parameters for the component from 1 to n.

4.4 Task 4: Conceptual Design & Prototyping

Task 4 for conceptual design and prototyping aims to not only confirm what possible forms of the target product in which requirements produced theoretically are reflected will be, visually, but also how they operate, physically and technically. In the representative FFE scenario, activity units, which have a phased relationship, were identified to exist. In the sequential relationship, concurrent collaboration *within* each activity unit was exposed, rather than the collaboration from *between* units which were revealed in Tasks 1 and 2. In the case of performance method units, as with Task 2, a common pattern was observed in the different performance methods offered by each interviewee, resulting in deducing a representative performance method. However, unlike Task 2 in which a single representative method is applied to all activities, the type of performance method here was different depending on each activity, resulting in different common patterns for each of the different activities. A representative method was thus devised for each activity, based on the common pattern.

4.4.1 Toolkits for Contextual Performance in Task 4: Conceptual Design & Prototyping

The purpose of Task 4 is to visually, physically and technically check the possible form of the target product in which requirements considered theoretically in Task 3 are reflected. With a functional embodiment of the underlying concept, the structure of Task 4 was developed as an extension of that of the previous task (Task 3), as shown in **Figure 18**. The y axis of Task 4 was designed to begin from requirements arranged on a component basis, enabling interlocking with the previous task (Task 3). The x axis was sequentially structured with the following four activity units (consisting of phased toolkits for performance method units): 1) Activity 4.1: *the principal designs*, where the initial simple form, using basic form architypes and geometry, are devised for each component (Performance Methods 4.1.1 and 4.1.2) and those simple forms are interjoined by applying the basic frame of the product, producing the initial principal concepts of the product (Performance Methods 4.1.3 and 4.1.4), 2) Activity 4.2: *the schematic designs*, where the initial principal concepts devised from the previous activity unit are modified by applying the function and system structure and the technical dimensions (Performance Methods 4.2.1 and 4.2.2), 3) Activity 4.3: *the styling designs*, where those variations are elaborated with 2D and 3D drawings (Performance Methods 4.3.1 and 4.3.2), and 4) Activity 4.4: *the prototype design*, where soft, hard and working prototypes are manufactured (Performance Methods 4.4.1 and 4.4.2).

Table 16. Quotes of contextual performance in Task 4 for conceptual design & prototyping

Participants	Quotes
P16	"… the conceptual design is to confirm the product design visually before going to the actual embodiment of the NPD … to visually identify how the product will look like if we develop the product based on the requirements …"
P02	"… by reflecting the requirements … in the first step, we devise the basic … principal concept by using various figures for each part of the product. Using those figures help us not only understand principal conceptual form simply but also generate many concepts varied from each other … in the next step, we reflect the function and system structure in each principal concepts

	… in this step we also mark dimensions on those concepts as a schematical design work … As doing the final work, we refine those schematic concepts to have more look like the real product form … we call it a styling work …”
P13	“… we usually use a particular phased-techniques … in the order of simple concepts with simple shapes, schematic concepts with possible dimensions, and refined concepts with actual form …”
P25	“… we apply each spec in each dismantled part one by one, generating partial product concepts. Then, we integrate them into a single concept … do it again, considering the structure of product function and system… finally, we elaborate the concept closer to the actual product … with hand drawing and 2D and 3D computer aided programmes such as illustrates, Rhino, Solidworks …”
P20	“… we design the concept of the product in the following systematic way … firstly, we devise rough concepts by synthesising rough form of each part … secondly, we embody function and system structure in the rough concept … finally, we do refinement the concept …”
P27	“… through a prototype, we practically check various aspects which were theoretically treated in the conceptual design stage …”
P03	“… after the concept design phase, prototyping can be done to confirm how the product can be operated physically, functionally and technically … in the first stage, in order to confirm the physical proportions of each part of the product, we produce soft mock-up …”
P17	“… for checking the product’ exterior … the soft mock-up can be manufactured by iso-pink, then hard mock-up very closer to a real product can be made with formboards and paints …”
P26	“… manufacturing and testing working prototype is the final work … this is a key work … by reflecting the workable system structure in the inside of the hard mock-up”

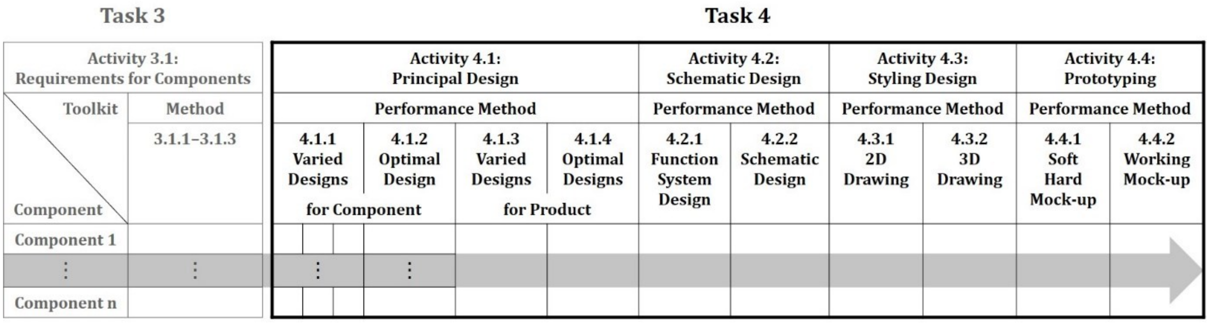

Figure 18. Contextual performance in Task 4 for conceptual design and prototyping

In this phased systematic manner, once initial simple forms for each component are devised, with the requirements reflected, a schematic and styling of the conceptual design for the whole product, along with prototypes, can be produced, in serial order.

4.4.2 Toolkits for Concurrent Collaboration in Task 4: Conceptual Design & Prototyping

Table 17. Quotes of concurrent collaboration in Task 4 for conceptual design & prototyping

Participants	Quotes
P11	“… we do concurrently check the form, function and technical operation of the product from the viewpoint of the four functional domains …”
P23	“… whether concept designs are feasible from the visual aspect and whether prototypes are feasible from the physical, functional and technical aspect are confirmed simultaneously by most of the performers involved in the given project …”
P36	“… generate concepts and manufactured prototypes should be checked from diverse functional domains ‘views …”

As with the requirements list task (Task 3), concurrent collaboration within toolkits of activity units was fostered here too by adopting Mechanism 2.2. Whether requirements have been effectively applied to conceptual designs and prototypes can be concurrently confirmed from the viewpoints of four functional domains (see **Table 17** and **Figure 18**).

4.4.3 Execution Concept for Task 4: Conceptual Design & Prototyping

Table 18. Schematic chart of Task 4 for conceptual design and prototyping

Component	Requirement $\boldsymbol{R_k}$	Various design for component $\boldsymbol{V_k(i)}$	FIltering processing $\boldsymbol{V_k(rC1)}$	Optimal design for component $\boldsymbol{C_k = R_k \times V_k(rC1)}$
Component 1	$O_1\, x\, I_1 = R_1$	$V_1(1)V_1(2)\ldots V_2(i)$	$V_1(rC1)$	$R_1 \times V_1(rC1) = C_1$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
Component n	$O_n\, x\, I_n = R_n$	$V_n(1)V_n(2)\ldots V_n(i)$	$V_n(rC1)$	$R_n \times V_n(rC1) = C_n$
Product	$\vdots$	$\vdots$	$\vdots$	$\vdots$
Component 1 + $\vdots$ + Component n	$R_k = \begin{vmatrix} R_1 \\ \vdots \\ R_n \end{vmatrix}$	$V_k(i) = \begin{vmatrix} V_1(1)\ldots V_1(i) \\ \vdots \\ V_n(1)\ldots V_n(i) \end{vmatrix}$	$V_k(rC1) = \begin{vmatrix} V_1(rC1) \\ \vdots \\ V_n(rC1) \end{vmatrix}$	$\{R_1 \times V_1(rC1)\} = C_1$ + $\vdots$ + $\{R_n \times V_n(rC1)\} = C_n$

$r =$ *The number of optimal principal designs,* k *= component No.,* $1 \le k \le n$

The structure of Task 4 is outlined in a schematic chart, as shown in **Table 18**. This schematic chart can be depicted by the equations as follows (5) (6):

$$\sum_{k=1}^{n} C_k$$

$$= \textstyle\sum_{k=1}^{n} R_k \times V_k(rC1) \ (5)$$

$$= \sum_{k=1}^{n} (O_k \times I_k) \times V_k(rC1)$$

$$= \textstyle\sum_{k=1}^{n} (o_k^m + o_k^u + o_k^a + o_k^e) \times (i_k^m + i_k^u + i_k^a + i_k^e) \times V_k(rC1) \ (6)$$

This formula presented in the second line (5) represents that conceptual designs (and prototypes) are the assemblage of optimal visual, functional, and technical conceptualisations (embodiments) of each requirement, on a component basis. The formula shown in the final line

(6) represents the underlying theoretical concept behind executing an overall FFE phase. The FFE execution can be regarded as a vision of a new product that can be embodied by assembling components in which requirements comprised of opportunities and their realisation methods, derived from the market-driven, user-driven, aesthetic-and-symbol-driven, and engineering-driven studies are optimally conceptualised from a visual, functional, and technical perspective.

4.5 A Data-driven FFE Model and FFE Execution Concept

A data-driven FFE model was developed for the entire FFE, through various deployment of toolkits, with consideration of contextual performance and concurrent collaboration. The model was constructed with a performative structure wherein qualitative and quantitative parameters produced in the configured toolkit set can interlock for contextual performance and concurrent collaboration from beginning to end.

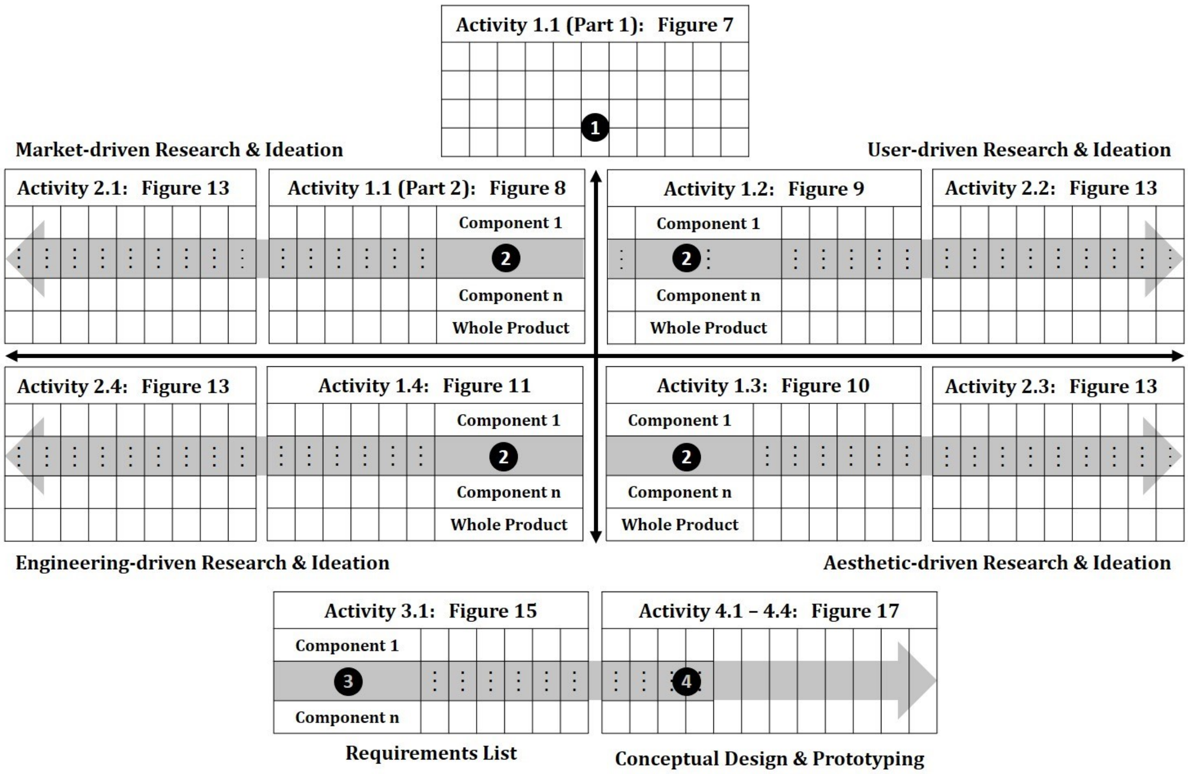

Figure 19. Data-driven FFE model

As seen in **Figure 19**, through use of a series of toolkits interlocked for contextual performance and concurrent collaboration, the parameters required in the FFE phase can be contextually as well as multidimensionally produced in Tasks 1 and 2 (❶❷), and integrated into the form of a parameters list in Task 3 (❸), and finally transformed into physical, functional, and technical form in Task 4 (❹). Consequently, all parameters can interlock with each other from the beginning right through to the end of the model. Once the initial toolkit produces parameters, the parameters can be consecutively obtained from the remaining toolkits, generating conceptual designs and prototypes as the final outcome of the FFE.

Based on the performance structure of the model and its operating mechanisms, each mathematical theory for performing each FFE task was extrapolated, and those theories were summarised with a single mathematical theory indicating the underlying theoretical concept of the entire FFE's execution (7):

$$\sum_{k=1}^{n}(o_k^m + o_k^u + o_k^a + o_k^t) \times (i_k^m + i_k^u + i_k^a + i_k^t) \times V_k(r\text{C}1) \quad (7)$$

o = opportunity, i = ideas, m = market-driven, u = user-driven, a = aesthetic-driven, e = engineering-driven
V = variations of conceptual design, r =the number of variations, k = component No., $1 \leq k \leq n$

5 Discussion and Conclusion

This study inferred the representative FFE scenario by analysing various real-world FFE scenarios from the viewpoints of contextual performance and concurrent collaboration. This representative scenario was embodied into the data-driven FFE model structured with toolkits integrated for contextual performance and concurrent collaboration. From reasoning behind the performance structure and operation mechanism of the model, the FFE execution concept consisting of mathematical basis was produced. Expected contributions to the effects of using the FFE model and execution concept are outlined as follows.

5.1 Use of the Data-driven FFE Model

- Using the model with the performative structure activating parameter-driven design, users can process and determine qualitative and quantitative parameters on a component basis, from the viewpoints of contextual performance and concurrent collaboration, unlike most previous models which are action-driven models at each step of the procedural structure.
- This contextual performance and concurrent collaboration enable users to explicitly understand the purpose, roles, and meanings of toolkits and parameters produced, and their relationships, in not only a single functional domain but also multidimensionally across diverse functional domains: the model enables the transfer of input and output parameters processed from toolkits across the model platform so that parameters from one user (or team) can be seen and used by others (or other teams), thereby providing effective contextual performance and concurrent collaboration. This facilitates users to understand the execution of each toolkit from viewpoint of the system as a whole and not just the constituent parts of the system.

In this regard, the underlying issue is that some people might regard the data-driven model as difficult to use due to the complexity of the model's structure. However, distinctive features can be explained by comparing it with other performative models using the matrix approach, e.g. Quality Function Deployment (QFD) and Design Structure Matrix (DSM), a comparison which yields the following two points: Firstly, output parameters produced in the previous models have difficulty with processing qualitative parameters (text and images) for the descriptive evidential interpretations and their contexts of the produced parameters. Instead, the models are useful for ascertaining the status of parameters with the numerical or semantic type, '1 to 9' or 'O' and 'X'. Secondly, parameters obtained in previous FFE models have trouble linking to each other. Users would only understand separate toolkits, and even then, only the ones that they themselves use. The reason for this is that the target research and analysis elements presented in the $x-$ and $y-$axes in the matrices appear to be selected and arranged based on what users expect, instead of being configured in advance for contextual performance and concurrent collaboration. Therefore, output parameters are limited by the expectations of users and thus the guaranteed inter-connectedness of parameters for contextual performance and concurrent collaboration cannot be infinite. For the two reasons, even with the same matrix-type, the previous models can be more complex for users.

- This enables decreasing uncertainty caused by obtaining an insufficient quantity of parameters from missing the use of the required toolkits and ambiguity incurred by an incorrect analysis of parameters from interpreting parameters fragmentarily. This can result in reducing iterative modification work and associated considerable time and cost savings. Previously, parameters obtained from each toolkit would exist independently and thus much incomplete and defective.
- Consequently, it is expected that those high quantity and quality parameters can make more details in product development, and those details can make a big difference in the outcomes of product development. Product development of today is becoming upward equalisation from the viewpoints of product's function, technical performance and aesthetic design. Therefore, infusing details and difference into the product can be one of the success factors.

5.2 Use of the FFE Execution Concept

- Each theory can be used as basic theoretical concept for performing each FFE task.
- An overall theory wherein each theory is integrated can be utilised as an underlying theoretical concept for the whole FFE execution.

To conclude, the data-driven FFE model can serve as practical functional performance guidance. When there is a demand for intensive FFE execution for particular activities or performance methods, the corresponding toolkit sets can be extracted selectively and used concentrically. Also, the partial, as well as the whole range of the FFE execution concept can serve as theoretical conceptual performance guidance for intensive FFE task performance or for full FFE implementation when employing the model.

6 Limitations and Future Research Direction

There are principal potential limitations, as follows:

- With the research motivation and purpose, literature review in this study is focused on exploring the past and current phenomena where few FFE toolkits have been devised considering contextual performance and concurrent collaboration, rather than establishing a grounded theoretical framework (theoretical positioning) used in the typical literature review method. Therefore, a systematic literature review method 'bibliometrics' is used. In the future research for validating the data-driven model developed, the typical literature review method is planned for theoretical positioning.
- Considering the research aim and direction, we followed Stake's case study method [34] under constructivism [35] rather than Yin's [36] and Eisenhardt's [38] methods under positivism [35]. Hence, the pragmatic concrete form of the data-driven FFE model was able to be developed. However, diverse types of theoretical conceptual FFE models are planned to be developed by using Yin's [36] and Eisenhardt's [38] case study methods in future research.
- The main aim of our paper is to provide a pragmatic data-driven FFE model where users can process NPD-related parameters using a series of toolkits of the model itself, for contextual performance and concurrent collaboration. Using the model developed, users explicitly understand the purpose, roles, and meanings of toolkits and parameters produced, and their relationships, in not only a single functional domain but also multidimensionally across diverse functional domains. This research contributes to providing more direct

functional performance guidance for contextual performance and concurrent collaboration rather than grounded theoretical implication. In the future study, through the validation or application studies, theoretical conceptual FFE model can be derived, contributing to grounded theoretical implication where we can achieve useful new knowledge and associated theories.

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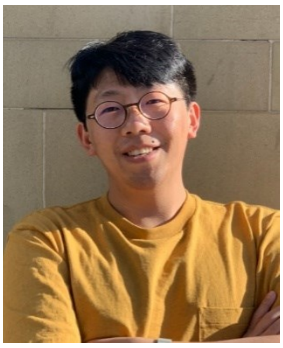
Biography

Dr Dongmyung Park earned a Doctorate in Design Engineering from the Dyson School of Design Engineering at Imperial College London. He has worked both at and with a number of global companies, including LG and Samsung Electronics, General Electrics, Braun, Philips, Jaguar and Rand Rover, and Rolls-Royce. He has extensive expertise in new product developments, in a number of roles, such as a design engineer, industrial designer, mechanical designer, design researcher, project leader and manager, and product development consultant, and in a diverse range of industrial sectors, including electronics, mobiles, home appliances, medical devices, electronic vehicles, and public transportation.



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